An Update on Design Tools for Optimization of CMC 3D Fiber Architectures

J. Lang and J. DiCarlo
NASA Glenn Research Center
Cleveland, Ohio

Research Supported by the
Supersonics Project
NASA Fundamental Aeronautics Program

Presented at 36th Annual Conference
on Composites, Materials, and Structures
Cape Canaveral, Florida, January, 2012

Background

- In recent studies, NASA has shown that there are multiple performance advantages in using 3D architectures for advanced SiC/SiC composites. These advantages primarily arise from the use of thru-thickness fibers that allow composites with *improved delamination resistance, improved impact resistance, and improved thru-thickness strength and thermal conductivity.*
- Another potential advantage for 3D architectures is improved matrix infiltration down the weaver fibers. Furthermore the use of 3D automation can possibly reduce manufacturing costs and scatter in composite properties due to the elimination of the human element that is typically involved in 2D tape and fabric lay-up techniques.
- However, for the most advanced SiC/SiC composites, the SiC fibers are stoichiometric in composition resulting in high bending stiffness. They also possess large nano-grains and associated rough fiber surfaces leading to poor abrasion resistance. These issues can enhance the probability of fiber fracture during 3D preforming and thus limit the available 3D architectural designs and thru-thickness fiber fractions.

Background (cont.)

- In the NASA architectural studies, it was also shown that if the matrix had reduced porosity, the in-plane matrix cracking strength of advanced SiC/SiC composites was controlled and predictable from the fiber tow geometric characteristics and volume fractions within the fiber architecture.
- This important observation initiated in-house studies aimed at developing user-friendly program and software tools that can be used for designing virtual 3D-woven architectures that will best meet the key fiber-controlled multi-directional property requirements of specific CMC components.
- Such fiber-controlled properties include the CMC in-plane and thru-thickness matrix cracking strength (MCS), ultimate tensile strength, creep strain , rupture strength, and thermal conductivity, as well as matrix infiltration paths and final matrix porosity.

Presentation

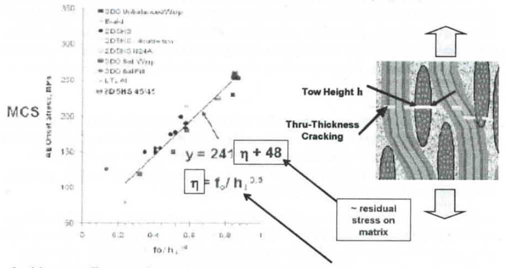
Objective: Describe and up-date progress for NASA's efforts to develop 3D architectural design tools for CMC in general and for SiC/SiC composites in particular.

Approach/Outline

Describe past and current sequential work efforts aimed at:

- Understanding key fiber and tow physical characteristics in conventional 2D and 3D woven architectures as revealed by microstructures in the literature
- Developing an Excel program for down-selecting and predicting key geometric properties and resulting key fiber-controlled properties for various conventional 3D architectures
- Developing a software tool for accurately visualizing all the key geometric details of conventional 3D architectures
- Validating tools by visualizing and predicting the internal geometry and key mechanical properties of a NASA SiC/SiC panel with a 3D orthogonal architecture
- Applying the predictive and visualization tools toward advanced 3D orthogonal SiC/SiC composites, and combining them into a user-friendly software program

NASA Physics-Based Design Tool for Predicting Architecture Effects on AE-measured MCS for Dense SiC/SiC



Key Architecture Factors Controlling Multi-Directional MCS:

f_0 = effective fiber volume fraction in test direction

= f (0° stuffers) OR = [f (+/-θ weavers)] [cos (θ)], whichever largest

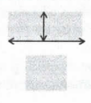
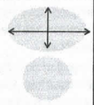
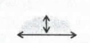
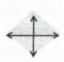
$h_\perp$ (mm) = maximum height of tows perpendicular to test direction

Key Fiber and Tow Modeling Parameters as Measured from 2D and 3D-Woven CMC Micrographs in the Literature

Fiber Type	Sylramic (also iBN)	ZMI	Nicalon	Nextel 720
Single Tow Fiber Count (N_f)	800	800	500	400
Avg. Fiber Diameter (d), µm	9.7	11.0	14.1	12.5
~ Fiber Area in Single Tow (A_f), mm²	0.059 mm²	0.081 mm²	0.078 mm²	0.049 mm²
~ Min Area of Single Tow (A_o) assuming 0.60 packing factor	0.10 mm² (155 mil²)	0.135 mm² (210 mil²)	0.13 mm² (200 mil²)	0.08 mm² (125 mil²)
~ Natural Lay-Down Width (w*) for (n) Bundled Tows: $w^* = 4d\,(n\,N_f)^{0.5}$	1.10 (n)^0.5 mm	1.25 (n)^0.5 mm	1.26 (n)^0.5 mm	1.00 (n)^0.5 mm

Note: Lay-down width (w*) only applies when the tow ends/per/inch allows a tow spacing larger than w*

Key Tow Shapes and Dimensions in 2D and 3D Woven Architectures

Tow Shape	Rectangular (also square)	Elliptical (also circle)	Half Lenticular	Diamond
Tow Schematics				
Typical Architectures where Tow Shape will appear	3D orthogonal and angle interlock: stuffers and weavers	2D fabric: stuffers	3D orthogonal and angle interlock: surface stuffers	3D angle interlock: warp and fill stuffers
Tow Height (h) x Tow Width (w) for (n) bundled tows (Total Tow Area = n A_o)	hw =1.0 (n A_o)	hw =1.3 (n A_o)	hw ≅1.4 (n A_o)	hw ≅ 2.0 (n A_o)

NASA Excel Tool to Calculate Key Fiber-Controlled Properties of 3D Fiber Architectures

3D Architecture	Architecture Type	Nominal Weaver Angle, degrees	Final Weaver Angle, degrees	Nominal RUV Height, mils	Final RUV Height, mils	RUV Width (across warp), mils	RUV Length (across fill), mils
Thru-Thickness Interlock	3	30	32.1	62	58	73	186

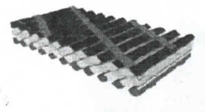
	Fiber Type	Number Bundled Tows	Tow Shape	Tow Aspect Ratio	Planar Gap, mils	Planar ends per RUV	Tow Height, mils
Warp Stuffer Tows (Fiber a)	1	1	1	8	0	1	4.5
Warp Weaver Tows (Fiber b)	1	1	1	10	0	1	3.9
Fill Stuffer Tows (Fiber c)	1	1	1	1.7		6	13.4
Fill Weaver Tows (Fiber d)	0						

User selects data for yellow cells to yield key properties:

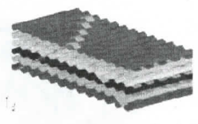
	Warp Weaver			Largest Perpendicular Tow Height, mm			AE Thru-Thickness Cracking Strength, MPa		
	R min, mm	Center θ	Eff. Vol. % at θ	X	Y	Z	X	Y	Z

National Aeronautics and Space Administration

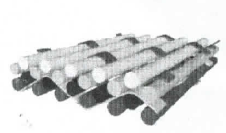
NASA Computer-Based Visualization Tool for Basic 3D Architecture Types



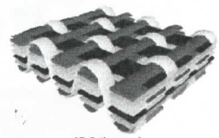
Through Thick Angle Interlock w/o Warp Stuffers



Through Thick Angle Interlock w/ Warp Stuffers



Ply-to-Ply Angle Interlock

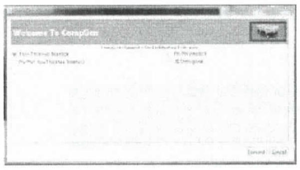


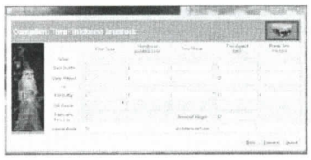
3D Orthogonal

www.nasa.gov

National Aeronautics and Space Administration

CompGen Software Package being developed for Design and Visualization of CMC 3D Architectures



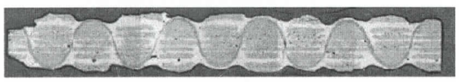


www.nasa.gov

National Aeronautics and Space Administration

Current Architectural Approach and Rationale

- There are multiple ways one can design a 3D fiber architecture. To assure accuracy in the design tools while at the same time achieving some practical results, our initial approach has been to focus on simple 3D orthogonal architectures.
- On the practical side, these architectures best allow us to keep the in-plane warp and fill stuffer tows to be straight, while allowing control of the thru-thickness weaver fiber volume fraction and reinforcement angle in the center of a CMC component wall where interlaminar stresses are envisioned to be maximum due to thermal gradients.
- Design and visualization tools were recently validated using a CVI-MI SiC/SiC panel with this 3D Orthogonal architecture:

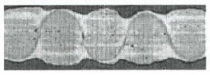


www.nasa.gov 11

National Aeronautics and Space Administration

Key Design-Tool Predictions for NASA 3D-Orthogonal CVI-MI SiC/SiC Microstructure with Sylramic Stuffers and ZMI Fiber Weavers

	Repeating Unit Volume Dimensions, mm			Total Fiber Volume, %		
	H	W	L	Warp Stuffer	Fill Stuffer	Warp Weaver
Predicted	1.9	3.0	1.4	14.3	17.4	3.3
Measured	2.0	3.0	1.4	15.2	17.4	3.2



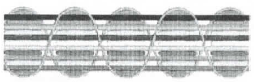
	Warp Weaver			Largest Perpendicular Tow Height, mm			AE Thru-Thickness Cracking Strength, MPa		
	R min, mm	Center Θ	Eff. Vol. % at Θ	X	Y	Z	X	Y	Z
Predicted	0.6	77°	3.0	0.12	0.17	1.4	119	122	26
Measured	0.5	75°	—	0.12	0.17	1.4	126	119	—

www.nasa.gov 12

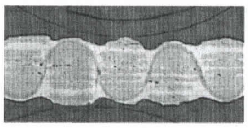
National Aeronautics and Space Administration

NASA Tool for Static Visualization of 3D-Orthogonal SiC/SiC Microstructure with Sylramic Stuffers and ZMI Fiber Weaver

Design Tool



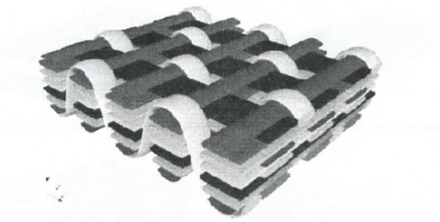
Actual

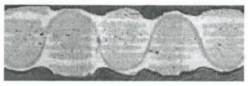


www.nasa.gov

National Aeronautics and Space Administration

NASA Tool for Rotating Visualization of 3D Orthogonal SiC/SiC Microstructure with Sylramic Stuffers and ZMI Fiber Weaver





www.nasa.gov

National Aeronautics and Space Administration

Current and Future Activities

- **Employ our design tools to seek and demonstrate 3D architectures for SiC/SiC turbine vanes with high total fiber fraction and with directional fractions dictated by the vane service requirements.**

- **One key goal is to determine architectural design and preforming approaches that will allow successful replacement of ZMI warp weaver tows with the stronger and more thermally conductive Sylramic-iBN fiber.**

- **Continue to upgrade our design tools by creating a user-friendly "CompGen" software package that incorporates all of our 3D design, prediction, and visualization programs.**

www.nasa.gov